IoT-Based Intelligent Energy Management for EV Charging Stations

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***Abstract*—The electronics panels and controllers used in electric vehicle (EV) charging stations need to function securely and optimally in countries such as India, where the external temperature remains high for a significant part of the year. This study is the first to use a solar-battery storage integrated switchable glazing architecture to supply HVAC (heating, ventilation, and air conditioning) in the control rooms of electric vehicle charging stations throughout the day. The EV charging station has been equipped with a rooftop-mounted solar PV source as part of an initiative to promote renewable energy and sustainable forms of mobility. The utilization of a vanadium redox flow battery (VRFB) by the system ensures energy security through the provision of a durable solution for storing energy over an extended period of time. A smart scheduling system utilizing IoT technology was demonstrated to effectively meet the glazing load need of buildings in real-time, taking into account dynamic climatic conditions. This system incorporates solar PV, VRFB storage, and the neighborhood power grid. The efficiency of the suggested method was validated using four separate transitory scenarios: sunny, intermittently cloudy, prolongedly cloudy, and low solar radiation with frequent grid outages. Due to its versatility to be applied in various situations, the suggested method has the potential to greatly enhance capacity.**

***Index Terms*—Internet of Things, Smart energy management system, Vanadium Redox Flow Battery, air conditioning system and electric vehicle.**

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I. Introduction

THE worldwide transition to sustainable energy solutions requires novel strategies for generating, storing, and using energy. This article examines the combination of solar energy with VRFB technology, along with smart building glazing, to develop an effective energy management system. This system is designed to meet the energy needs of EV charging stations while also maintaining appropriate inside air conditions through the integration of smart HVAC technology [1]. The increasing demand for Electric Vehicles (EVs) has accelerated the need for efficient and sustainable EV charging infrastructure. As governments and industries push towards electrification and renewable energy, traditional charging stations face challenges, such as high energy consumption, grid dependency, and substantial operational costs. In addition to charging EVs, these stations require energy for ancillary services such as heating, ventilation, and air conditioning (HVAC) systems, which are vital for maintaining user comfort in charging station facilities. Thus, optimizing energy usage for both EV charging and HVAC systems becomes a critical concern [2], [3]. Renewable energy integration, particularly through solar photovoltaic (PV) systems, offers a viable solution for reducing grid dependency. However, the intermittent nature of solar power demands effective energy storage mechanisms. Vanadium Redox Flow Batteries (VRFBs) have emerged as a promising technology for large-scale energy storage due to their scalability, long life cycle, and ability to store renewable energy efficiently. Paired with solar PV systems, VRFBs can store excess energy generated during peak sunlight hours and release it during periods of high demand or low solar availability, ensuring a reliable power supply [4]’ [5].

Another innovative technology that can significantly reduce energy consumption is switchable glazing, which dynamically adjusts the amount of sunlight and heat entering a building. By controlling the transparency of windows in real time, switchable glazing reduces the building’s heating and cooling loads, minimizing the energy consumption of HVAC systems. In the context of EV charging stations, integrating switchable glazing with renewable energy sources can further enhance energy efficiency [6], [7]. The integration of these technologies requires a sophisticated energy management system capable of optimizing the distribution and storage of energy. The Internet of Things (IoT) plays a pivotal role in this context by enabling real-time monitoring, data collection, and automated decision-making. IoT-based energy management systems can adjust energy flow between solar PV panels, VRFBs, switchable glazing, and HVAC systems based on real-time conditions such as weather, energy demand, and battery state of charge. This ensures that the energy usage of the EV charging station is optimized to minimize grid dependency and operational costs [8] – [10].

The Internet of Things (IoT) has revolutionized energy management systems by enabling real-time monitoring, control, and optimization of energy resources. In the context of EV charging stations, IoT devices such as smart sensors, meters, and controllers are used to collect data on energy generation, storage levels, and consumption patterns. This data is then processed by algorithms to optimize energy flow between renewable sources, storage systems, and energy loads such as EV chargers and HVAC systems [11] – [13]. Previous research has highlighted the benefits of IoT-based energy management systems in improving energy efficiency and reducing costs in smart grids and microgrids. These systems enable real-time adjustments based on changing energy demand, weather conditions, or battery charge levels. Additionally, predictive algorithms can forecast energy usage patterns and make proactive decisions to ensure that the system operates at optimal efficiency, reducing energy waste and improving the overall sustainability of the charging station [14] – [17]. Several studies have explored the integration of renewable energy and energy storage systems in EV charging stations. Aan energy management system for EV charging stations using solar PV and battery storage, focusing on reducing grid dependency through optimized energy scheduling. Other works have examined the use of demand-side management and load forecasting techniques to balance energy supply with real-time demand. While these studies have contributed valuable insights, most have focused primarily on energy generation and storage aspects without addressing the potential energy savings from the building infrastructure, particularly HVAC systems.

Furthermore, the integration of switchable glazing in energy management strategies has been underexplored in the context of EV charging stations. Although some work has investigated the use of smart building materials for reducing energy consumption in residential and commercial buildings, the combination of switchable glazing with renewable energy and energy storage systems in EV charging stations is a novel approach. This paper seeks to fill this gap by proposing a comprehensive IoT-based smart energy management system that integrates solar PV, VRFB, and switchable glazing to optimize energy usage for both EV charging and HVAC systems [18], [19]. This paper builds on existing research by integrating multiple advanced technologies—solar PV, VRFB [20], switchable glazing, and IoT—to create a unified energy management framework for EV charging stations. By focusing on the combined optimization of energy flow for EV charging and HVAC systems, this work addresses the broader challenge of reducing operational costs and enhancing energy efficiency. The IoT-based control system ensures real-time decision-making, leveraging data from various sources to dynamically balance energy supply and demand [21], [22].

II. METHODOLOGY

The research approach delineates the procedure for conceptualizing, executing, and evaluating the suggested intelligent energy management system. This encompasses the process of choosing and determining the appropriate size of solar panels, configuring the Vanadium Redox Flow Battery (VRFB), installing Internet of Things (IoT) sensors, and incorporating switchable building glazing. The text discusses both simulation and real-world testing approaches. The methodology section provides a detailed explanation of the methodical process employed to create, execute, and assess the suggested IoT-based smart energy management system, which integrates solar energy, Vanadium Redox Flow Battery (VRFB) technology, and switchable building glazing. This study utilizes a comprehensive approach to guarantee the strength of the system and the accuracy of the findings [23], [24]. The proposed IoT-based smart energy management system for EV charging stations integrates renewable energy sources, advanced energy storage, dynamic building materials, and real-time monitoring to optimize energy usage. The system architecture consists of several key components, each contributing to a sustainable and efficient energy flow. These components include solar photovoltaic (PV) panels, vanadium redox flow batteries (VRFB), switchable glazing, and IoT-enabled sensors and controllers [25] – [27]. The following subsections detail the system's architecture, energy flow, and interaction between these components. Simulation tools are utilized to create a model and simulate the proposed system in several circumstances, enabling virtual testing and optimization. Field testing is carried out at a prototype electric vehicle charging station that is fitted with the integrated energy management system. This stage entails the continuous monitoring of the system's performance for a prolonged duration, evaluating its ability to adjust to changing energy demands, and measuring the effects on HVAC systems using switchable building glazing control [28], [29]. The data collected from both the simulation and real-world testing phases undergo thorough scrutiny. Evaluations are conducted on key performance parameters, including energy efficiency, system responsiveness, and the capacity to satisfy electric vehicle charging requirements. Comparing simulated and real-world results allows us to gain insights into the practical feasibility of the system and identify potential areas for enhancement [30].

The results obtained during the analysis phase are used to continuously improve the system through iterative optimization. Modifications are implemented to algorithms, control techniques, and hardware configurations in order to optimize overall performance. This iterative process guarantees ongoing enhancement and flexibility in response to diverse environmental and operational circumstances [31], [32]. This methodology guarantees a methodical and comprehensive investigation of the suggested IoT-based intelligent energy management system. By combining simulation and real-world testing, a comprehensive assessment of the system's performance can be achieved, leading to well-informed judgments and recommendations.

III. AN INTELLIGENT ENERGY MANAGEMENT SYSTEM BASED ON IOT

It is presented in this section that an in-depth analysis of the components and architecture of the Internet of Things-based smart energy management system is described. The monitoring and control of energy storage, flow, and consumption are all subjects that are discussed in this paper. Some of the topics that are covered include communication protocols, sensor networks, and data analytics. We placed a strong emphasis on the adaptability of the system in order to fulfill the ever-changing energy requirements of electric vehicle charging stations. This project intends to incorporate solar energy, switchable building glazing, and technology known as Vanadium Redox Flow Battery (VRFB) in order to achieve the highest possible level of efficiency associated with electric vehicle (EV) charging stations. In addition to this goal, the major role of the heating, ventilation, and air conditioning system is to keep the room at a comfortable temperature and humidity level. Through the comprehensive integration of solar energy, virtual reality field beam technology (VRFB), and switchable building glazing, it is possible to create a smart energy management system that is both versatile and adaptive, and that is based on the Internet of Things (IoT). This system is specifically designed for charging stations for electric vehicles. In the following, we will examine the results of the simulation, the data from the experiments, and the findings of the performance evaluations of the system in greater detail. Here is a high-level schematic illustration of the project that is being suggested, which may be found in Figure 1. A cutting-edge variation of glass that can be manipulated electrically has been installed in the control room of a charging station for electric vehicles recently. The capability of electrically triggered switchable electrochromic glass windows to transition from being entirely opaque to completely transparent in a very smooth motion is one of the most significant advantages of these windows. The assertions that were made in earlier study on the significant energy demand of the changeover to the electrically driven smart window have not been proven with any evidence. This study demonstrates the possible integration of renewable energy sources, such as VRFB storage, with energy-efficient electric vehicle charging stations and electrically controlled smart windows. Specifically, the research focuses on charging stations for electric vehicles.The utilization of renewable energy sources and environmentally responsible modes of transportation is encouraged by the placement of a solar photovoltaic (PV) source on top of an electric vehicle charging station. The vanadium redoX flow battery (VRFB), which is the system's dependable and long-lasting energy storage solution, ensures that the system's energy security is maintained. The distribution grid is the source of the electricity that is used at the charging station for electric vehicles. An optimum integration of distributed generating, storage in vanadium redox flow batteries (VRFBs), and photovoltaic (PV) systems is required. When it comes to properly controlling the power needs of building glazing loads in response to changing weather conditions and real-time data, a sophisticated energy management system is very necessary. In order to fulfill the energy requirements of intelligent building glazing, it is possible to utilize a scheduling system that is enabled by the Internet of Things (IoT) and combines solar photovoltaic (PV) technology, vanadium redox flow battery (VRFB) storage, and power from the local distribution grid. It is the overarching objective of this study to devise a plan that will make it possible for charging stations for electric vehicles to function in an effective and relatively inexpensive manner. This approach includes a kilowatt-scale Vanadium Redox Flow Battery (VRFB) storage device as well as an intelligent building glazing energy management system. Both of these components are essential components. The effectiveness of the proposed system was evaluated in four distinct temporary conditions: sunny, occasionally cloudy, always overcast, and low solar energy with frequent power disruptions. Each of these scenarios was used to evaluate the system simultaneously.

The system architecture is mostly made up of three primary components, which are as follows: At the charging station for electric vehicles, solar panels are positioned in such a way that they efficiently capture energy from the sun. When selecting solar panels, the most important factors to take into consideration are their potential capacity, efficiency, and compatibility with the location. Through the use of energy storage, a vanadium redox flow battery (VRFB) system is able to guarantee a continuous flow of electricity, even in the event that solar output is low or demand is high. Within the design of the VRFB, efficiency, scalability, and endurance were all taken into consideration. Intelligent windows that are equipped with switchable glazing technology are incorporated into the infrastructure of the charging station. These windows are equipped with sensors and controllers that allow them to manage the amount of light that enters the room as well as the amount of heat that stays within. Through the utilization of the Raspberry-Pi communication platform and the MODBUS via TCP/IP platform connection, we have been actively monitoring and managing the energy management system in real time. It has been decided to construct a primary server for the purposes of administration and tracking.

Taking a look at Figure 3 makes it abundantly evident that the MQTT protocol is utilized in order to establish the connection that is bidirectional. The usage of message-queue transceiver protocols, such as MQTT, is especially beneficial in circumstances where bandwidth is restricted. MQTT gives you the ability to read and publish data from sensor nodes, as well as tell them to change their outputs. You may also use it to read data from sensor nodes. As a consequence of this, it is not difficult for various devices to exchange data with one another. In addition to being able to regulate the output through command communication, it is also able to read and publish data that is acquired by sensors. This capability is a significant advantage.

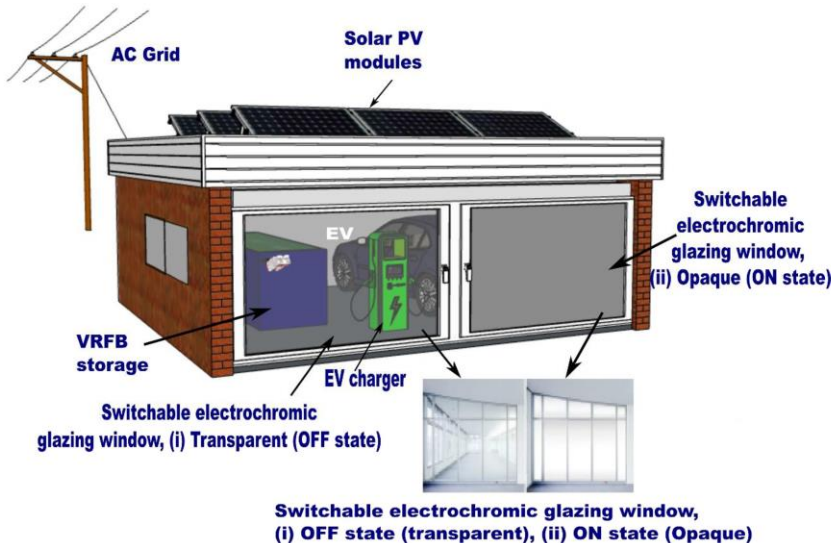

Fig. 1. A comprehensive diagram illustrating the proposed project

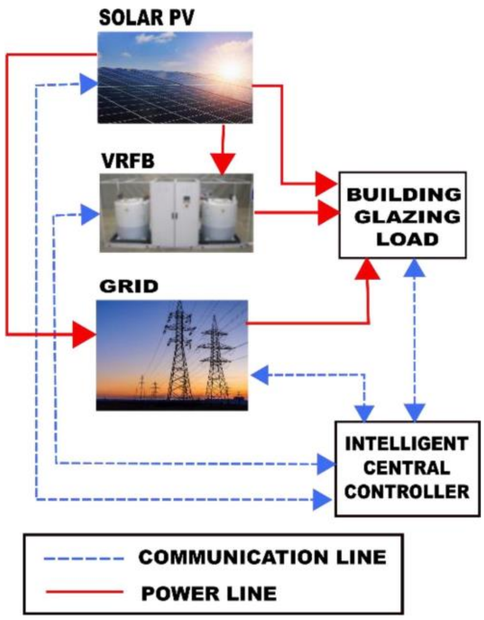

Fig. 2. Schematic depicting the step-by-step advancement of the proposed system

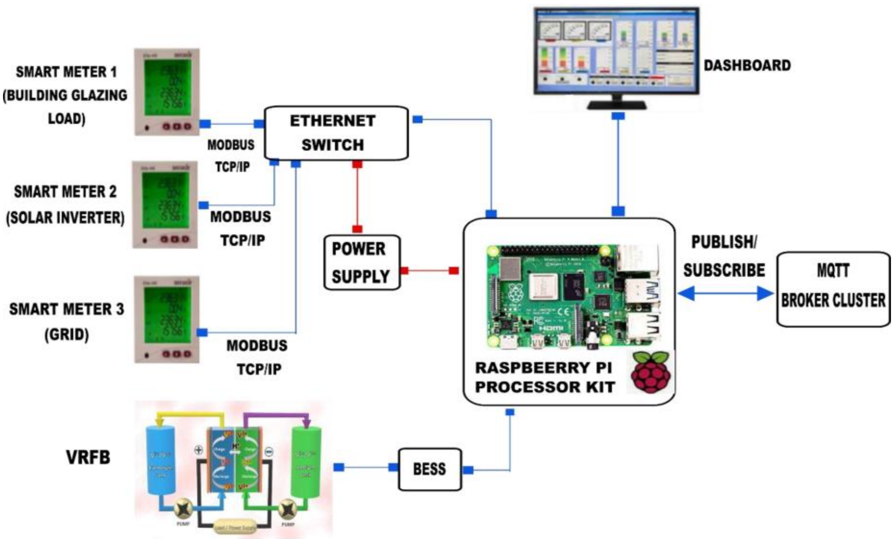

Fig. 3. Future-Framework Design Intelligent Communication System Built on the Internet of Things

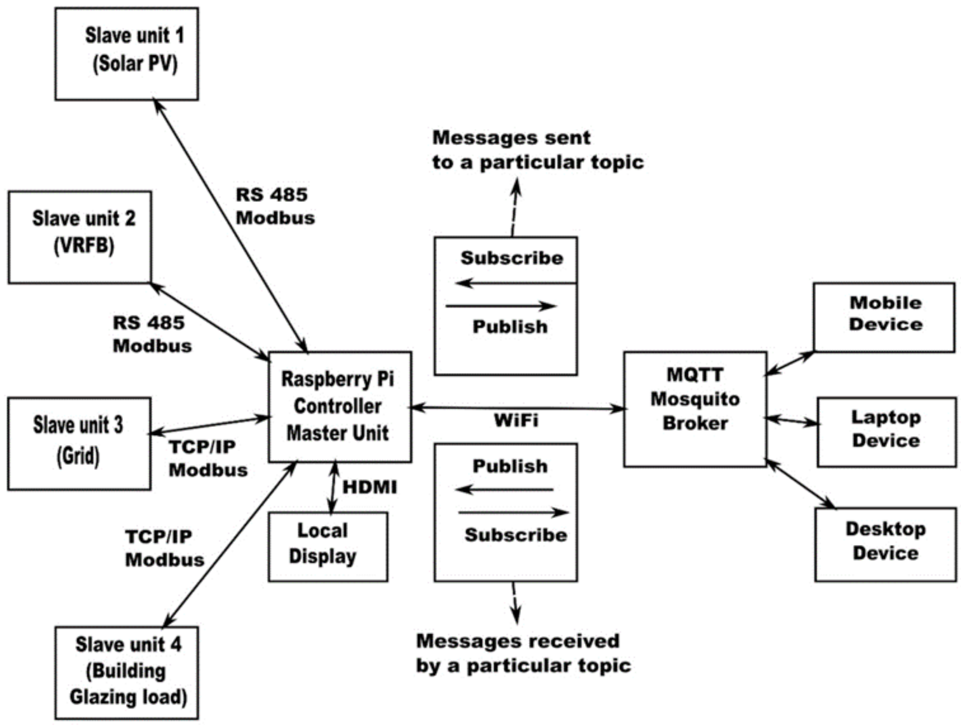

Fig. 4. Smart communication system's internal process flow based on the Internet of Things

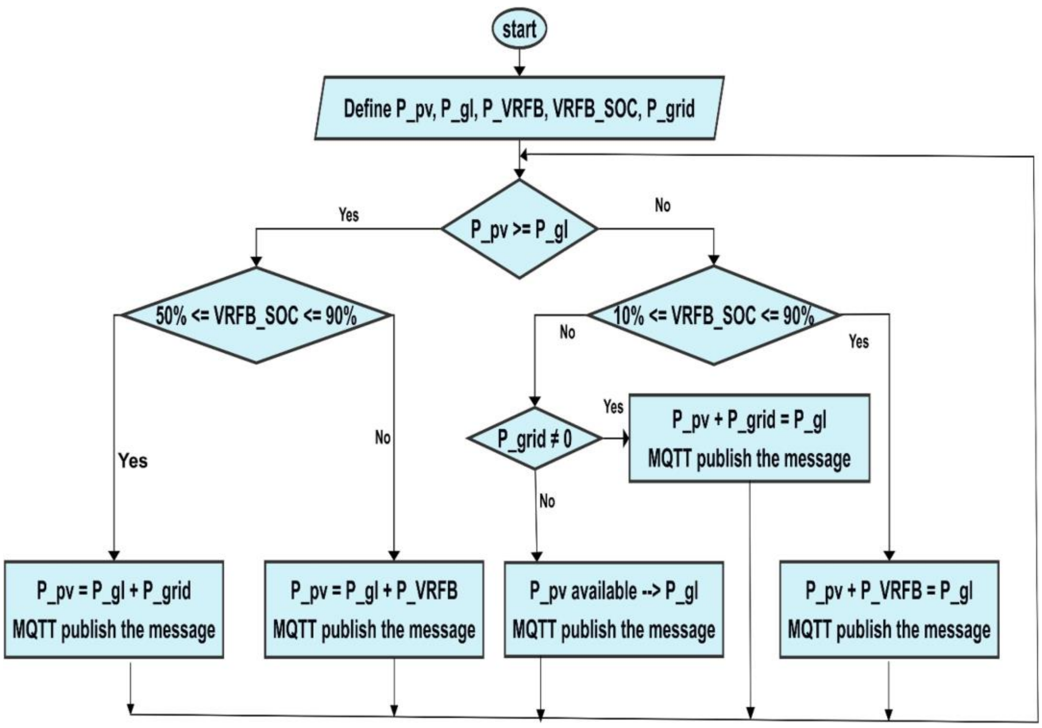

Fig. 5. Energy management strategies for smart building glazing

A smart communication system that is based on the Internet of Things is depicted in Figure 4, which is an internal flow diagram of the system. In Figure 4, we see a representation of the two-way MQTT communication that takes place between the mobile devices, laptops, and Raspberry Pi SBCs that comprise the Internet of Things smart communication system. This connection is made possible altogether by the mosquito broker. The Raspberry Pi Controller is largely responsible for monitoring and controlling the building's distribution grid, solar photovoltaic (PV) system, VRFB storage, and VRFB. Using this master controller, all of the subordinate devices are under its supervision. Either TCP/IP Modbus or RS 485 Modbus can be utilized to facilitate the transport of data between different devices. In order for a subscriber to take advantage of the broker's data, they are need to submit a SUBSCRIBE message that contains the appropriate subject. A PUBLISH message is transmitted to the broker whenever the publisher experiences a demand for data pertaining to an existing subject. Due to the fact that they maintain the session regardless of whether the devices are powered on or off, brokers are an excellent choice for handling intermittent connections. Message queuing and updates can be automated with MQTT, even when the device is offline, which is one of the most significant advantages of using MQTT rather than HTTP.

The internet of things-based vanadium redox flow battery (VRFB) technology powers the proposed smart energy management system. VRFBs are ideal for large-scale energy storage due to their scalability, cycle life, and efficiency. According to the fundamental principle, vanadium ions in different oxidation states perform an electrochemical reaction that stores and releases electrical energy. VRFB technology in the proposed system allows energy storage and efficient management to match electric vehicle charging station demand. Simulations and real-world testing will assess the VRFB system's performance to determine its role in ensuring a reliable energy supply in the following sections. Figure 5 shows a flow diagram for VRFB storage integrated EV charging stations with switchable building glazing load and smart energy management.

IV. Results and Discussion

The efficiency and effectiveness of the suggested approach are proven by the reported results of both simulations and real-world testing. Extensive simulations were used to evaluate the performance of the smart energy management system that was offered. This system is based on the internet of things (IoT). The outcomes of the simulation shed light on the manner in which the system adjusts to the ever-changing power requirements and environmental conditions, as well as its responsiveness and effectiveness. The results of the simulation demonstrate that the system optimizes the charging and discharging cycles of the VRFB circuit and makes effective use of solar energy during peak output, which ultimately results in a very low amount of energy consumption. The mechanism's nimbleness ensures that less energy is lost than would otherwise be the case. When it comes to controlling its energy consumption and production, the VRFB system is extremely efficient because to its design. By demonstrating superior voltage management and a smooth integration with solar energy, the simulations guarantee that the charging stations for electric vehicles will have a steady source of electricity. An actual solar PV-VRFB storage integrated electric vehicle charging station that includes switchable building glazing load need was used to successfully test the smart energy management algorithm that was provided as well as the Internet of Things-based smart communication system. For a period of ten hours, the proposed intelligent energy management algorithm was put through its paces by means of an actual load demand profile. In order to maintain the switchable glazing in the building, there is a continual load requirement of 500 W. When it comes to switchable building glazing, the demand profile has been taken into consideration during the integration of the distribution grid, solar photovoltaic (2 kWP), and VRFB storage. Figures 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15 each exhibit the results of four real-world case studies for smart energy management in bright, gloomy, and worst-case conditions, respectively. These figures are displayed in the order of their respective findings. In light of the fact that the fourth scenario illustrates the energy management algorithm's inability to fulfill the glazing load requirements of buildings as a result of limited solar PV availability and frequent grid disruptions, it is the most awful of the possible results.

Through the application of the smart energy management technique, the following outcomes were observed in four different weather case studies:

On a bright and clear day, the results of the smart energy management algorithm's monitoring of the system in the first case study are displayed in Figure 6. This monitoring took place from 06:00 to 16:00 when the sun was shining. Because there is a sufficient amount of sunlight, the switchable building glazing's load need of 500 W is completely satisfied by the power that is supplied by the solar module. Whenever the glazing load need is satisfied, the excess power from the solar photovoltaic panels is utilized to charge the VRFB storage, as shown in Figure 7. At eleven o'clock in the morning, the procedure is finished when the VRFB state-of-charge reaches ninety percent. Following the procedure of charging the VRFB storage and satisfying the glazing load need from buildings, the subsequent stage involves exporting excess solar photovoltaic power to the distribution grid. During the peak hours of solar insolation, which are from 10:00 to 16:00 hours, the power export reaches its highest point at a power output of 1000 watts at twelve o'clock, as depicted in Figure 6. In a setting with sunny weather, the VRFB SOC might be anywhere from fifty percent to ninety percent, as shown in Figure 7. Around eleven o'clock in the morning, the VRFB storage is obviously charged, and it remains in that state until sixteen o'clock. When the PV power source is not producing electricity throughout the night, the VRFB storage is able to meet the glazing load in an effective manner. Consequently, this indicates that there is the potential for efficient resource allocation and power self-sufficiency through the utilization of an intelligent energy management system.

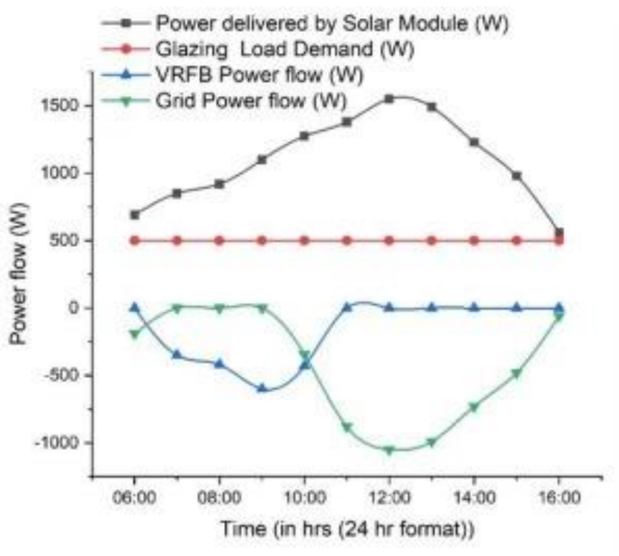

Fig. 6. Conditions characterized by abundant sunshine in the building's

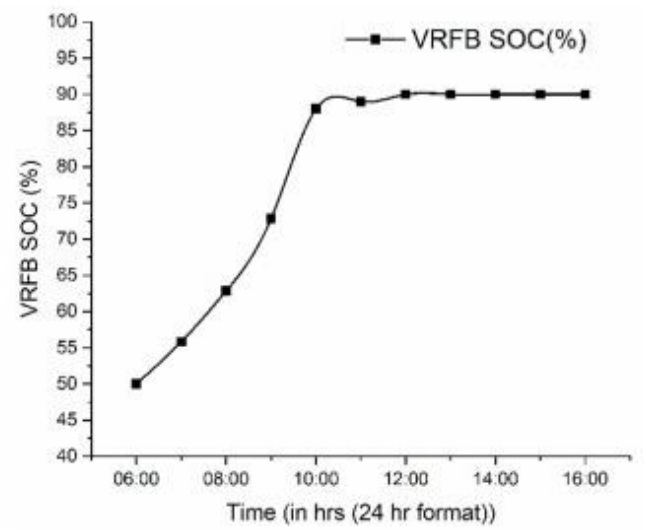

Fig. 7. Conditions with plenty of sunshine the state of charge (SOC) of the VRFB over time

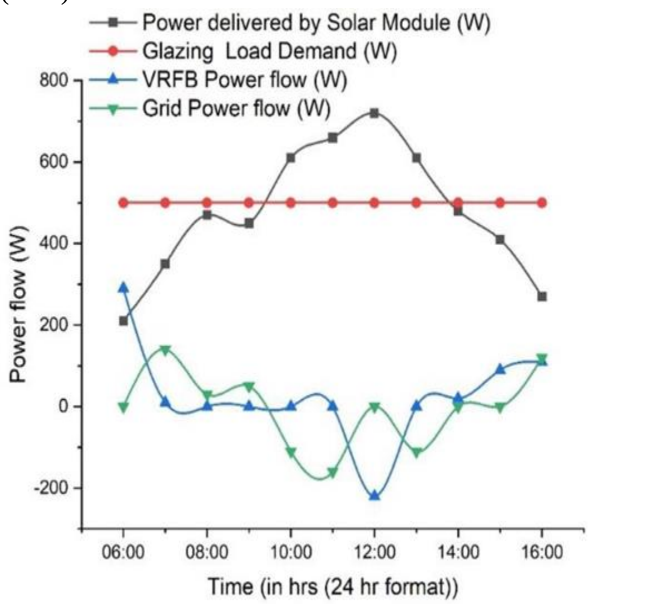

Fig. 7. Sunny weather sharing power between energy sources, storage, and the grid to meet building glazing load requirement

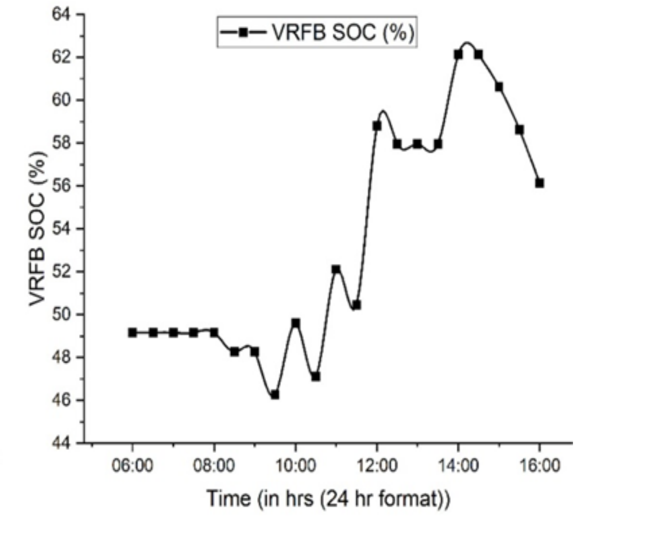

Fig. 9. Sunny weather VRFB SOC over time

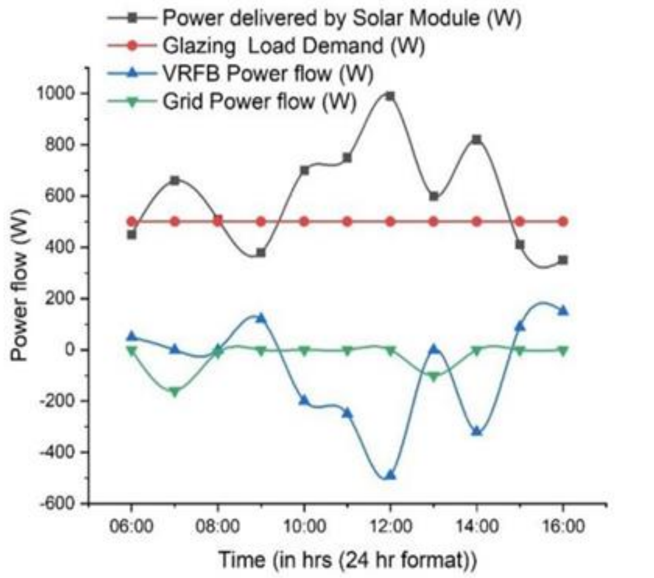

Fig. 10. Cloudy weather sharing power between energy sources, storage, and the grid to meet building glazing load requirement

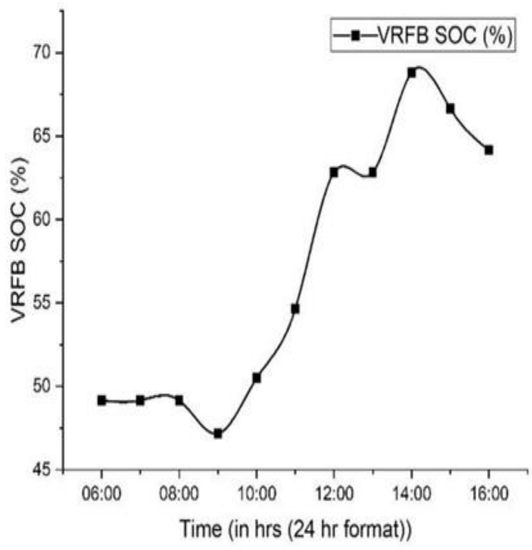

Fig. 11. Cloudy weather VRFB SOC over time

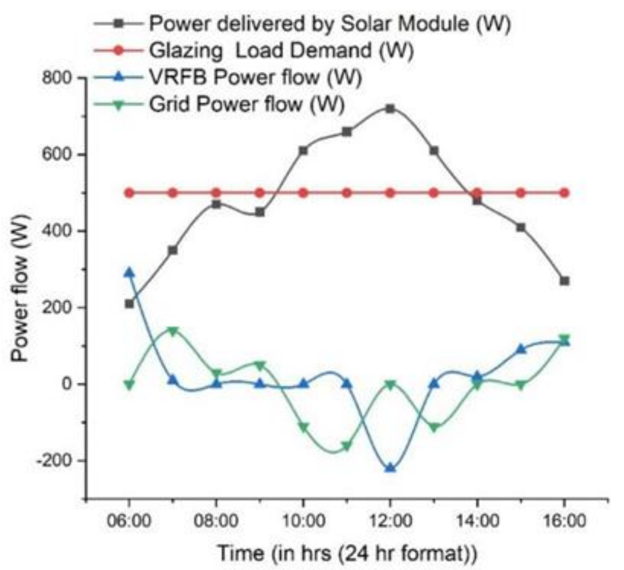

Fig. 12. Prolonged-cloudy sharing powers between energy sources, storage, and the grid to meet building glazing load requirement

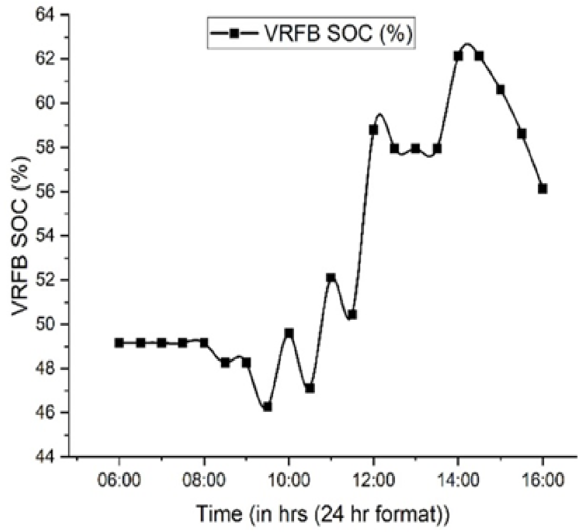

Fig. 13. Prolonged-cloudy weather VRFB SOC over time

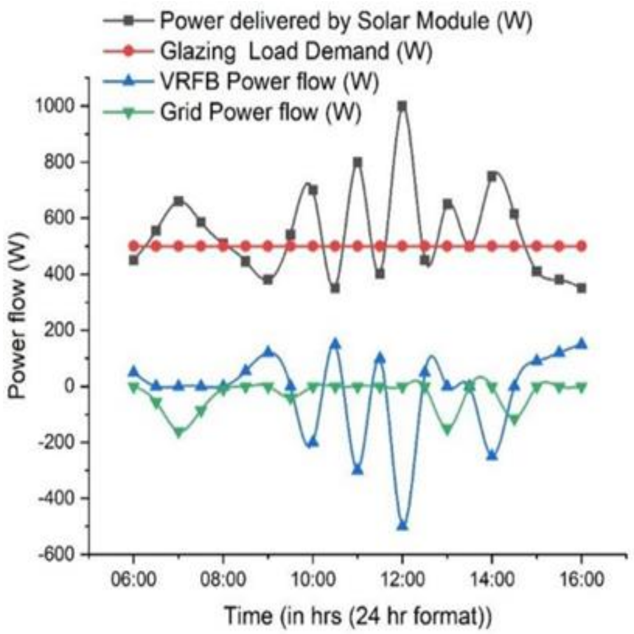

Fig. 14. 10 Worst case situation weather sharing powers between energy sources, storage, and the grid to meet building glazing load requirement

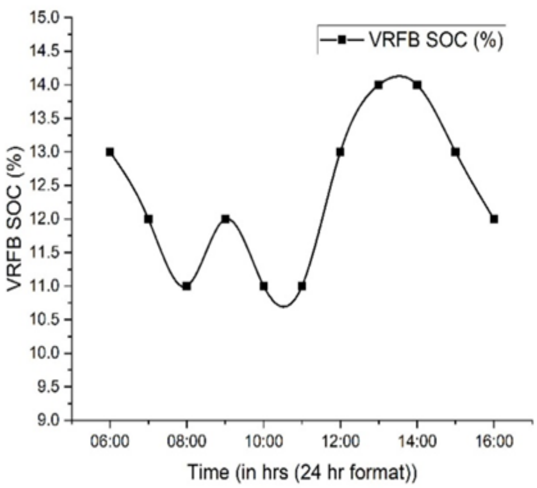

Fig. 15. Worst case situation weather VRFB SOC over time

Solar PV is the most essential of the currently available power sources for providing the glazing load requirement. The negative magnitudes of the VRFB power represent the VRFB storage charging process, as seen in Figures 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15. In contrast, a positive power magnitude indicates VRFB discharge, which is the inverse of what happens in the real world. Furthermore, when the distribution system detects an excess of solar PV power output, the excess electricity is sent back into the grid, and the magnitude of power coming in from outside sources is shown as negative.

V. Conclusion

The proposed IoT-based smart energy management system is a significant step towards sustainable and efficient energy solutions for EV charging stations. The combination of solar energy, VRFB technology, and switchable building glazing, enabled by IoT controls, provides a pragmatic and flexible solution to tackle the energy concerns of the future. This research establishes the foundation for ongoing investigation, advancement, and adoption of intelligent energy management systems that are in line with the worldwide transition towards a more environmentally friendly energy environment. The incorporation of solar energy, Vanadium Redox Flow Battery (VRFB) technology, and switchable building glazing into the Internet of Things (IoT) framework demonstrates a collaborative method for managing energy, enhancing the efficiency of energy generation, storage, and usage. The simulation findings demonstrate the system's exceptional ability to effectively utilize solar energy, efficiently operate switchable glass, and reliably maintain a stable power supply through the VRFB system.

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